



IN718 Additive Manufacturing Properties and Influences

JANNAF Conference, Nashville, TN
Session 3G - Additive Manufacturing for Liquid Propulsion I

Paper #3951
1 – 5 June 2015

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Acknowledgement

The list of people who have contributed to the additive manufacturing effort at NASA Marshall Space Flight Center is too long to recite, herein, and the opportunity to present the following information is appreciated.

- Propulsion Engineering
- Nonmetals Engineering
- Metals Engineering
- Materials Test Lab



Discussion Topics

- Material Information and Test Orientation
- Build Parameters versus Mechanical Properties
- Survey of Capabilities Across Vendors
- Conclusions and Next Efforts



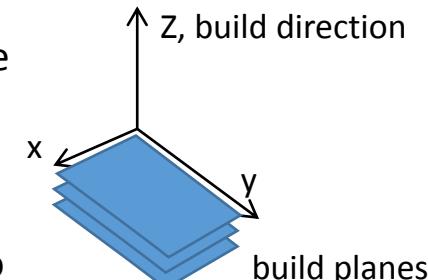
Material Information:

- The materials tested were IN718 nickel-base superalloy.
- Specimens were produced as a dedicated build or as representatives of the build lot where parts were produced.
- Two heat treat conditions are represented, and both received stress relief and hot isostatic pressing (HIP) processing, as follows:
 - Stress Relieve at 1950F, vacuum, 1.5 hours, then quench in argon.
 - Excise parts from build platen.
 - HIP 2125F, 15 ksi argon, 3 hours, furnace cool (4 hours).
- Some specimens received heat treat A: after stress relief and HIP* the following was performed
 - Homogenize 2150F, vacuum, 1 hour, quench to 1100F in argon in less than 10 minutes.
 - Solution treat and age per AMS 5663.
- Other specimens received heat treat D: after stress relief and HIP the following was performed
 - No homogenization step was performed.
 - Solution treat and age per AMS 5664.
 - Surfaces were either bead blasted or micro-machining processed (MMP) finished per a proprietary process.



Build Orientation:

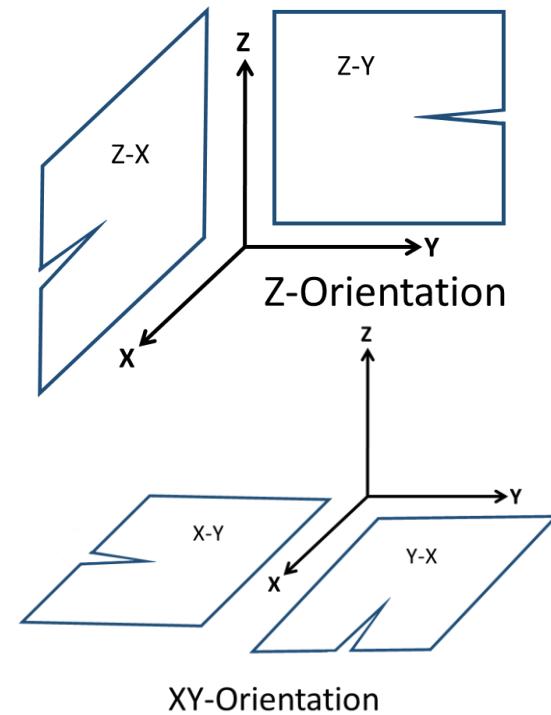
- The naming convention adopted at NASA-MSFC for additive manufacturing is shown in the figure on the right.
 - Z is the build direction, and XY is the build plane.
 - The material is transverse-isotropic, i.e., properties do not vary by direction in the build plane, and so the "XY" notation was adopted for any direction in the build plane.



Build Orientation

Test Orientation:

- The tested orientations were identified as Z- and XY-, and Z- corresponds with Z-X* or Z-Y orientations leading to delamination of adjacent build planes, while XY- corresponds to X-Y or Y-X orientations, leading to the tearing of the build plane.



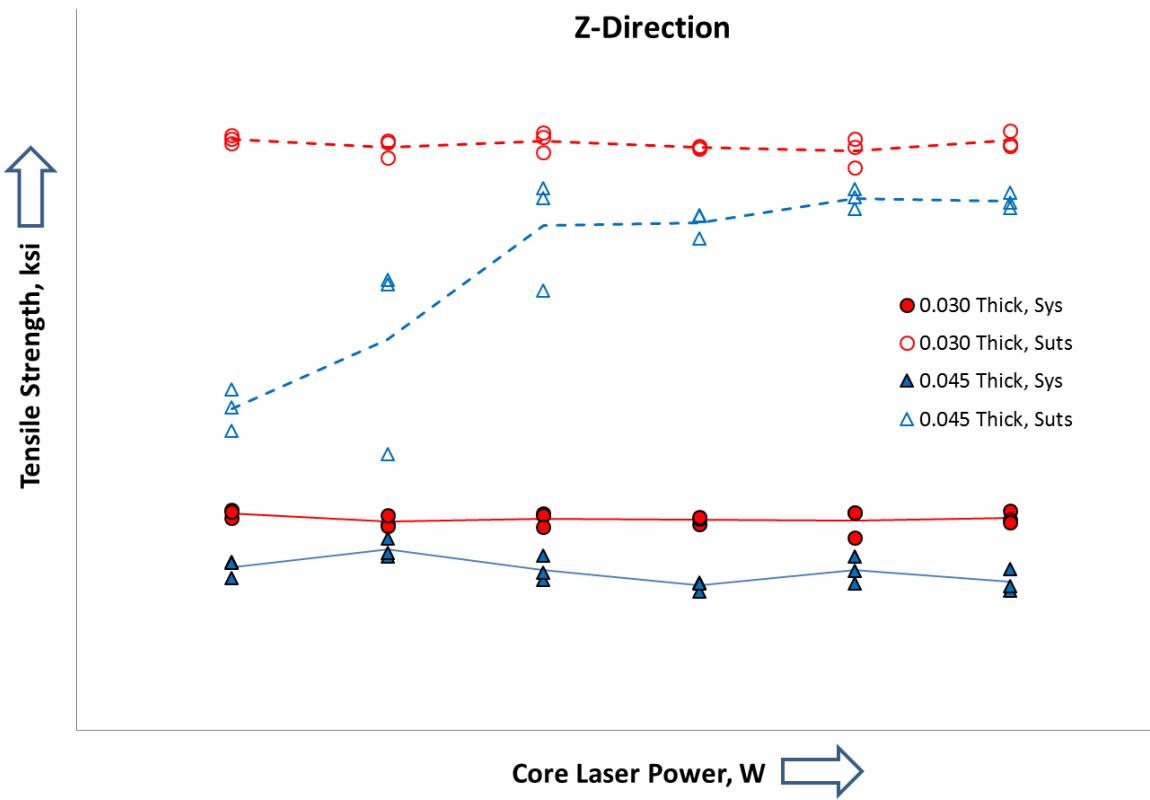
*This follows the ASTM naming convention, identifying the loading direction as the first digit(s), followed by the crack extension direction as the second digit(s).



The Effect of Build Parameters on Mechanical Properties



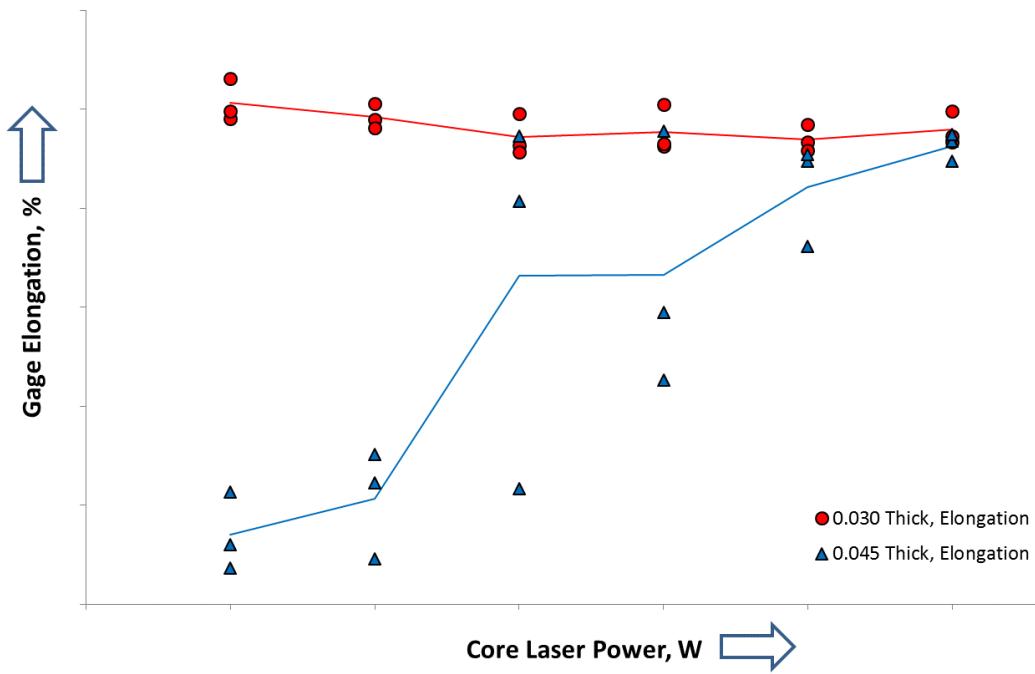
SLM Laser Power Investigation
IN718 Round Tensile Test Results
Z-Direction



- Graph of ultimate tensile and yield strengths versus core laser power. Two layer thicknesses were evaluated: 0.030-mm and 0.045-mm., and all build parameters were per recommendation while the power was varied around the recommended value.
- Notice that the ultimate tensile strength increases as input power increases for 0.045-mm ONLY. This seems to level off and variance decreases as power increased.



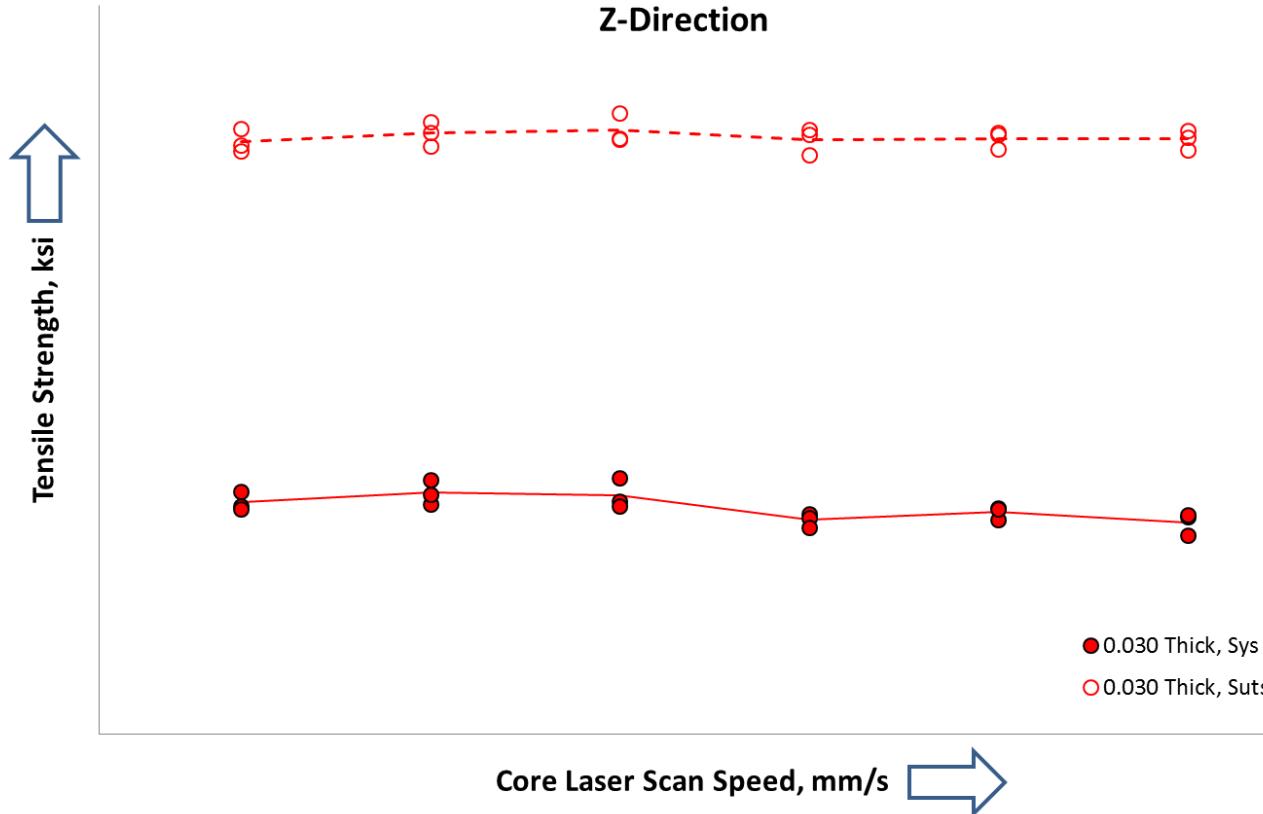
SLM Laser Power Investigation
IN718 Round Tensile Results
Gage Elongation, Z-Direction



- Graph of percent elongation versus core laser power. Two layer thicknesses were evaluated: 0.030-mm and 0.045-mm., and all build parameters were per recommendation while the power was varied around the recommended value.
- Notice that the gage elongation increases as input power increases for the 0.045-mm layer thickness ONLY.
- The two thicknesses seem to be converging towards the same value.



**SLM Laser Scan Speed Investigation
IN718 Round Tensile Test Results
Tensile Strength, Sys and Suts
Z-Direction**

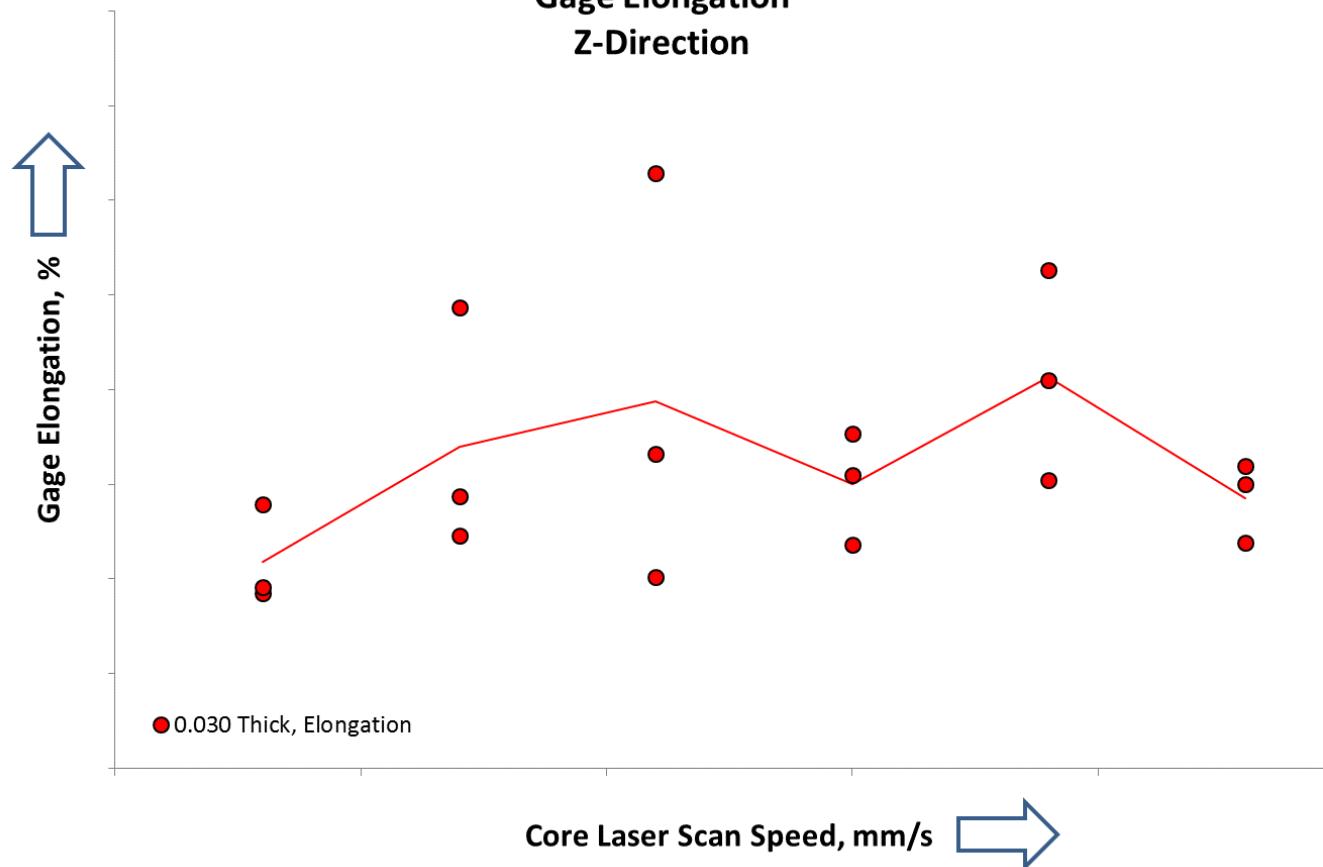


- All variables were as recommended, with laser scan speed varied around the recommended value.
- Ultimate tensile strength and yield strength were essentially constant over the entire range of laser scan speeds tested.



SLM Laser Scan Speed Investigation IN718 Round Tensile Test Results

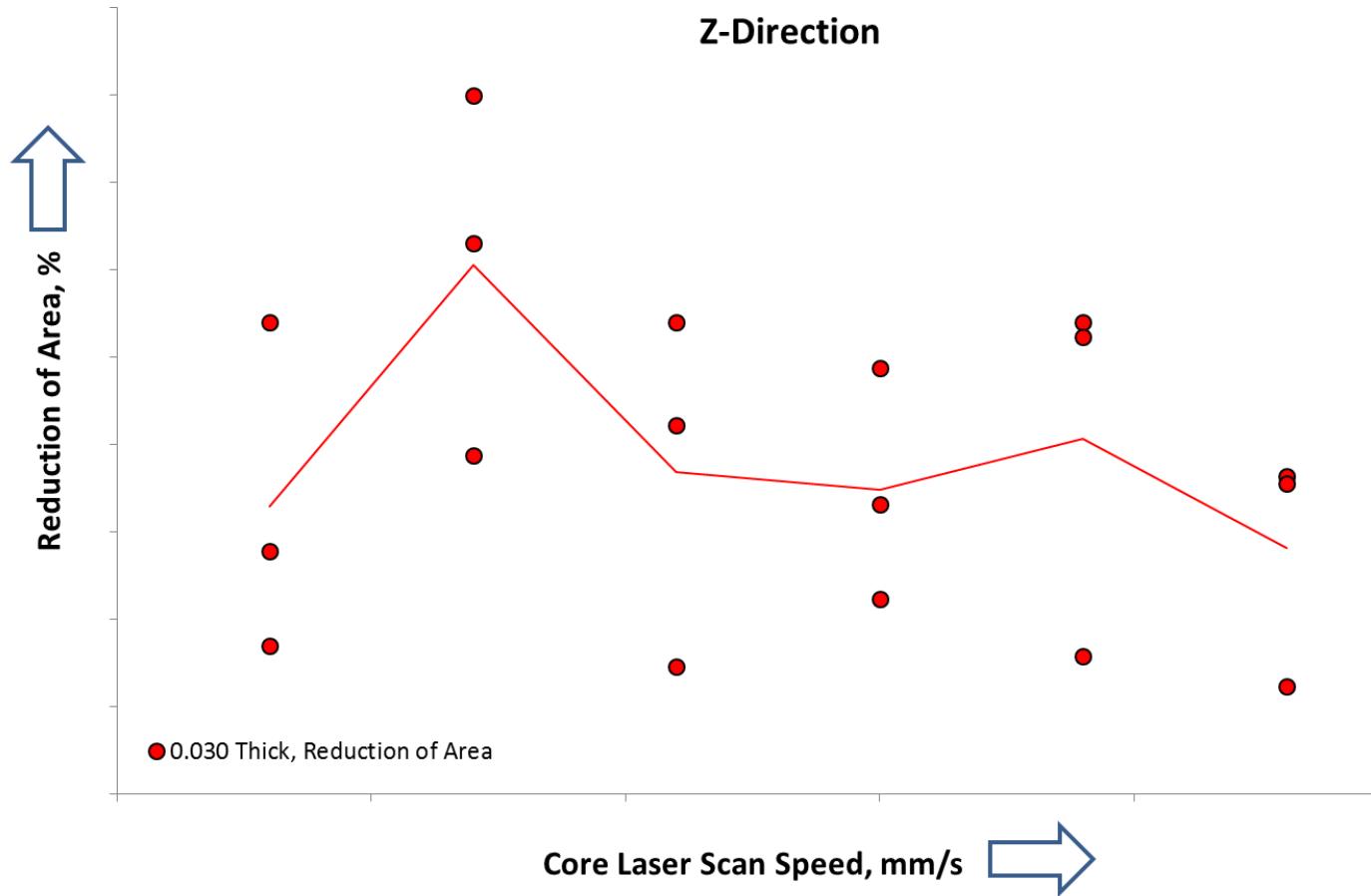
Gage Elongation Z-Direction



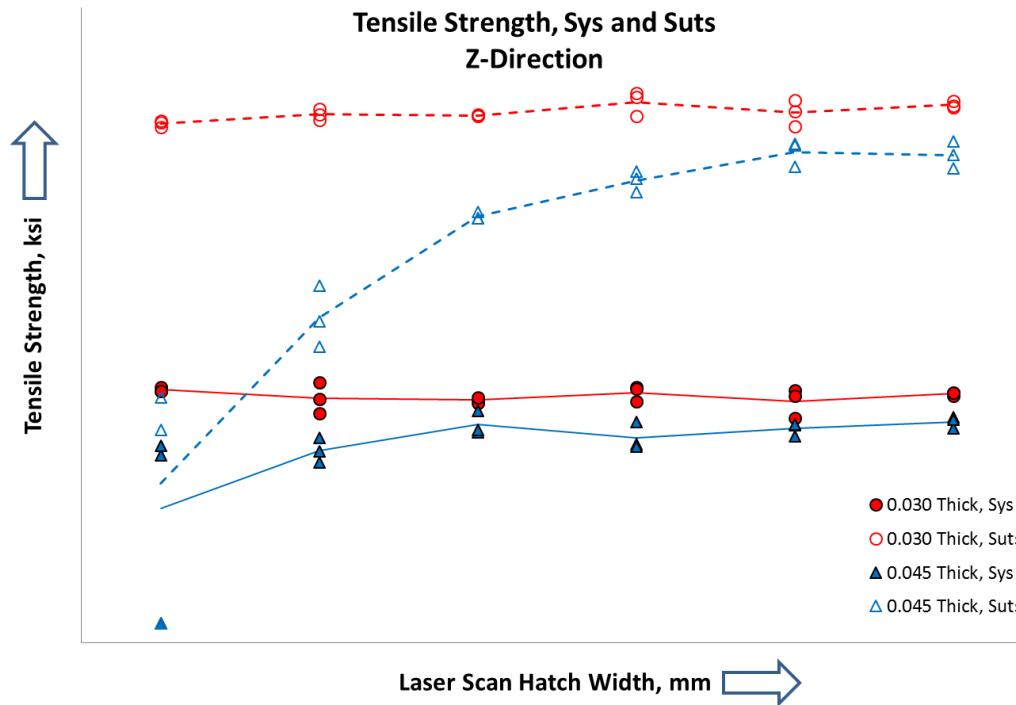
- All variables were as recommended, with laser scan speed varied around the recommended value.



**SLM Laser Scan Speed Investigation
IN718 Round Tensile Test Results
Reduction of Area
Z-Direction**

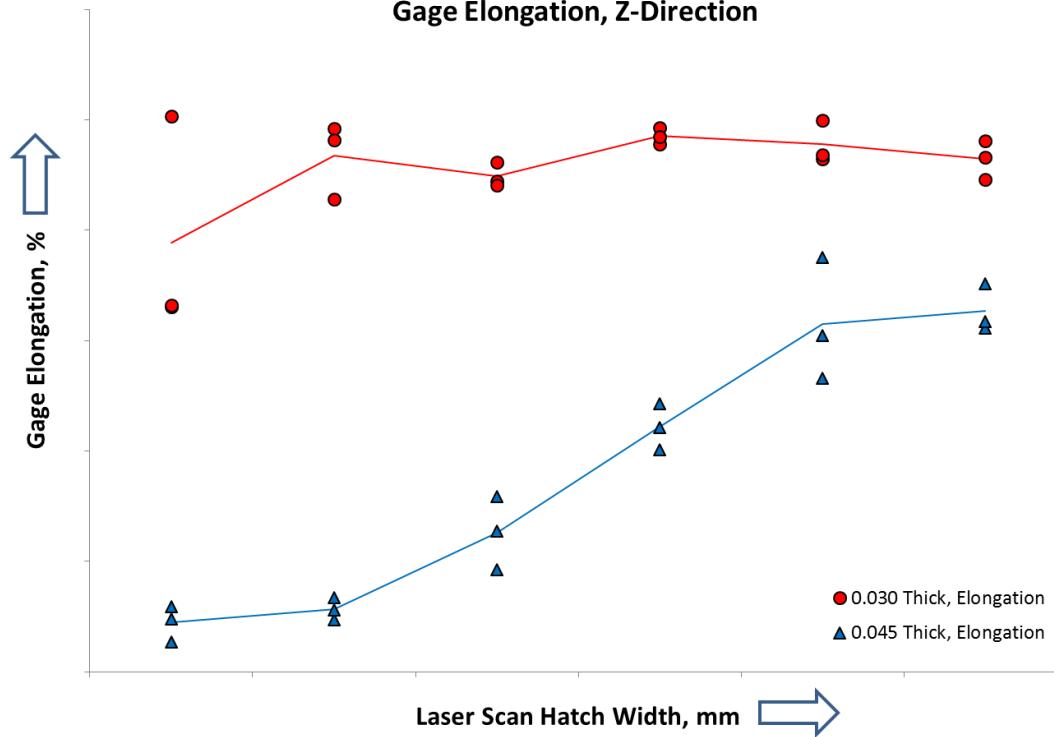


SLM Hatch Width Investigation
IN718 Round Tensile Test Results
Tensile Strength, Sys and Suts
Z-Direction

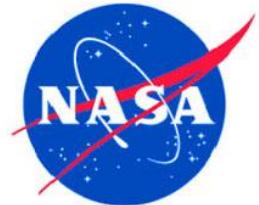


- Graph of ultimate tensile and yield strengths versus laser scan hatch width. Two combinations of layer thicknesses/core laser power were evaluated: 0.030-mm/180 watts and 0.045-mm/200 watts. Build parameters were set per recommendations, except for hatch-width, which was varied around the recommended value.
- Notice that the ultimate tensile strength increases as hatch width increases for 0.045-mm ONLY. This seems to level off and variance decreases to a level considered acceptable slightly above the recommended value.
- Yield strength may increase for the 0.045-mm build thickness to a stable value at a hatch width slightly below the recommended value.

SLM Hatch Width Investigation
IN718 Round Tensile Results
Gage Elongation, Z-Direction



- Graph of elongation versus laser scan hatch width. Two combinations of layer thicknesses/core laser power were evaluated: 0.030-mm/180 watts and 0.045-mm/200 watts. Build parameters were set per recommendations, except for hatch-width, which was varied around the recommended value.
- Notice that the gage elongation increases as hatch width increases for the 0.045-mm layer thickness ONLY.
- Gage elongation appears to increase slightly for the 0.030-mm layer thickness up to the recommended value, and has insignificant variance for increasing hatch widths beginning slightly below the recommended value.

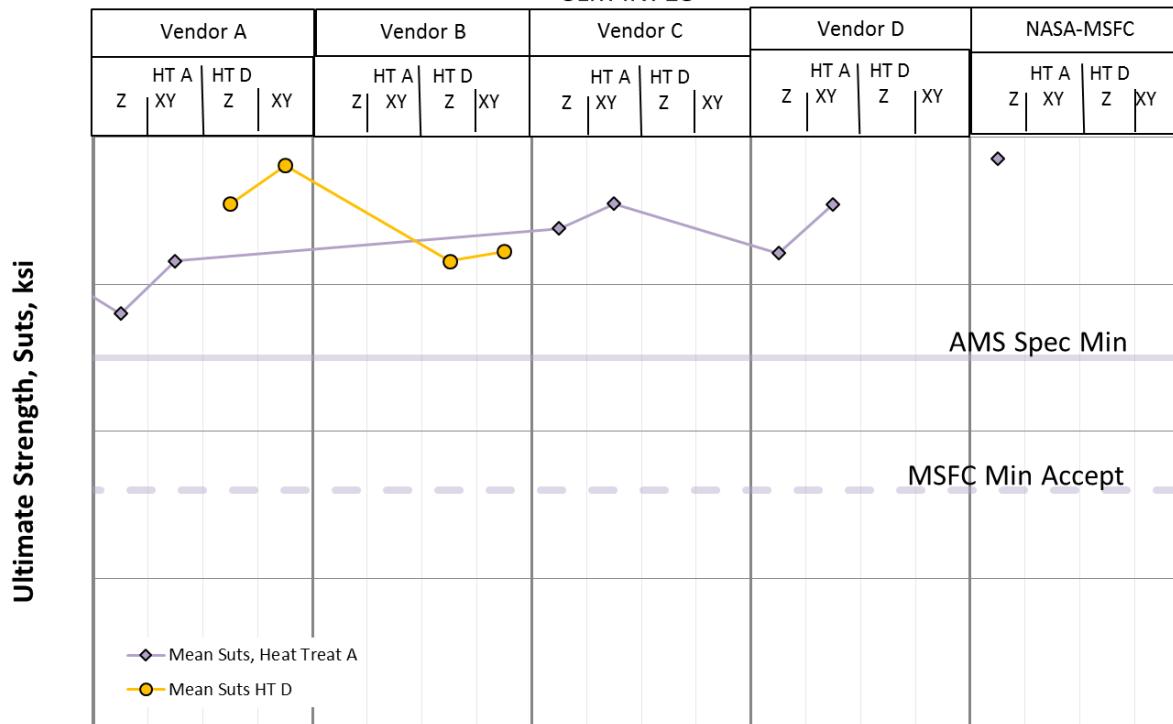


Survey of Capabilities across Vendors



Vendor Results--Room Temperature Tensile Tests

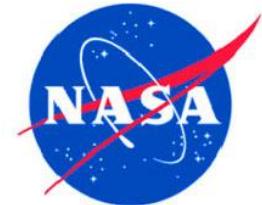
SLM IN718



NOTE: Each of these points is generated as an average of all of the like data available.

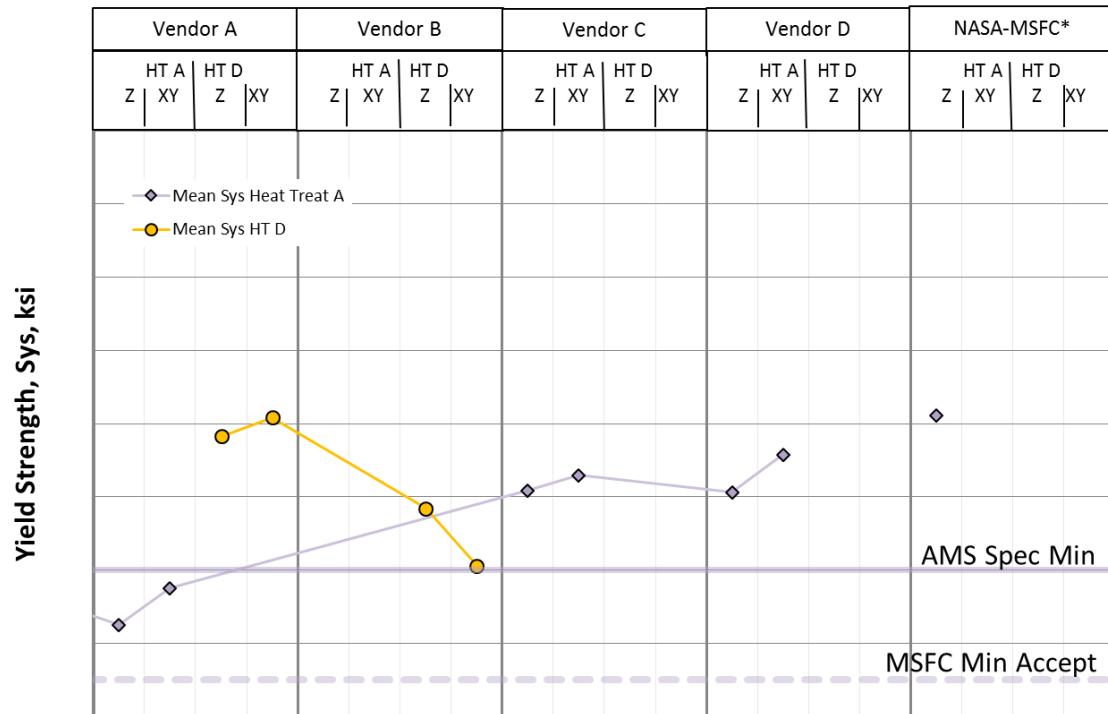
*NASA-MSFC tensile tests are 0.030" build thickness, coming from the laser power, scan speed, and hatch width trials.

- Z- and XY-orientations provided similar results for S_{uts} . The XY-orientation was slightly better.
- All data are above the AMS 5663/5664 minimum and the adopted MSFC minimum.



Vendor Results--Room Temperature Tensile Tests

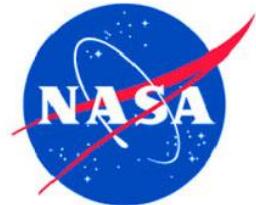
SLM IN718



NOTE: Each of these points is generated as an average of all of the like data available.

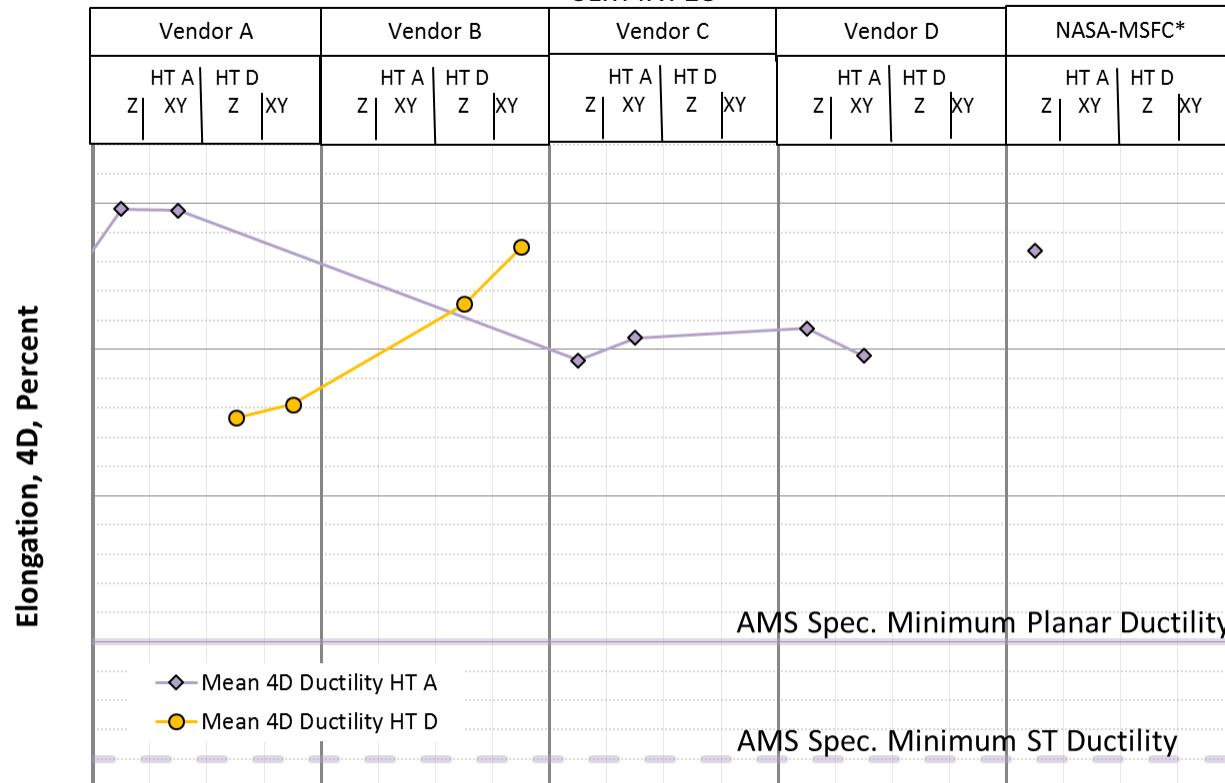
*NASA-MSFC tensile tests are 0.030" build thickness, coming from the laser power, scan speed, and hatch width trials.

- All S_{ys} results shown above are consistent with those provided for S_{uts} :
 - Z- and XY-orientations provided similar results for S_{ys} .
 - The XY-orientation was slightly better.
- Results for all but one vendor meet or exceed the AMS 5663/5664 value shown.



Vendor Results--Room Temperature Ductility

SLM IN718

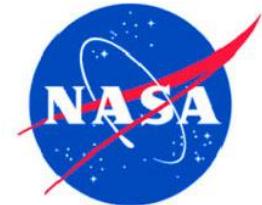


*NASA-MSFC tensile tests are 0.030" build thickness, coming from the laser power, scan speed, and hatch width trials.

NOTE: Each of these points is generated as an average of all of the like data available.

The AMS planar specification minima vary with direction (longitudinal or long-transverse), and the lower of these was selected for this comparison.

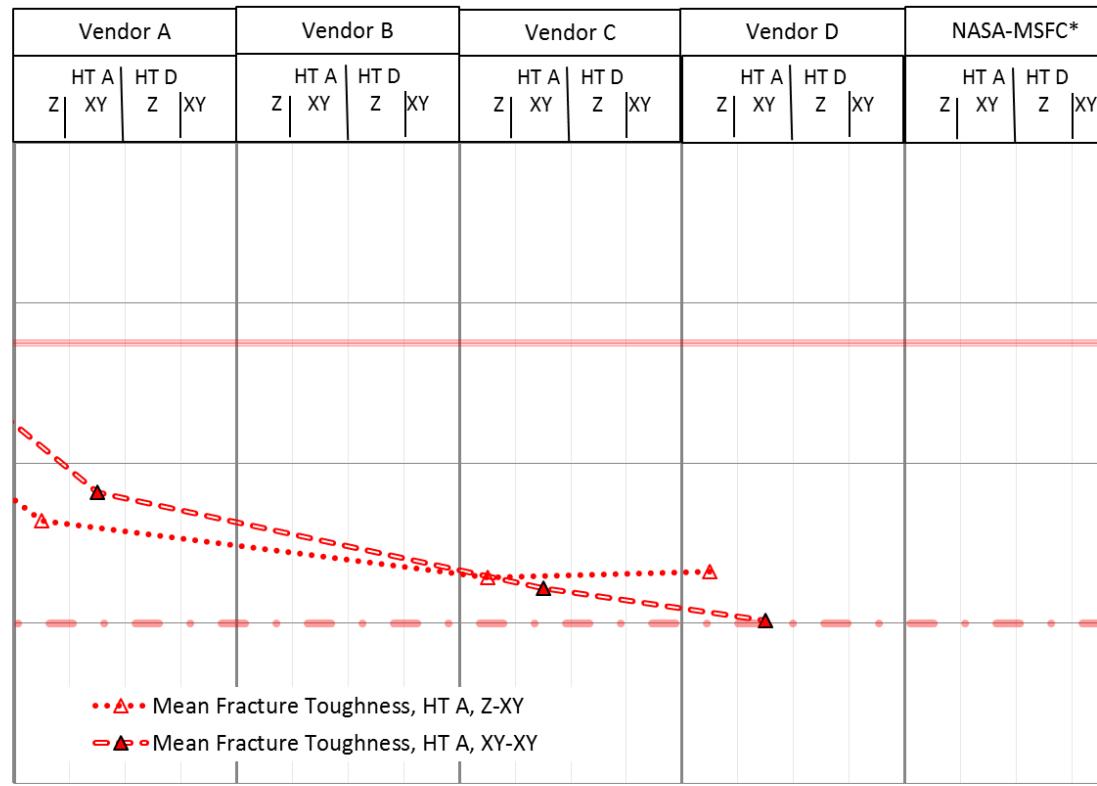
- The ductility results are well above the AMS specification minimums.



Vendor Results--Room Temperature Fracture Tests

SLM IN718

Fracture Toughness, K_{Iq} , ksi-sqrt(in)



NOTE: Each of these points is generated as an average of all of the like data available.

K_{Ie}

For fracture results shown, Z indicates the Z-XY orientation per ASTM E1820, while XY indicates the XY-XY orientation.

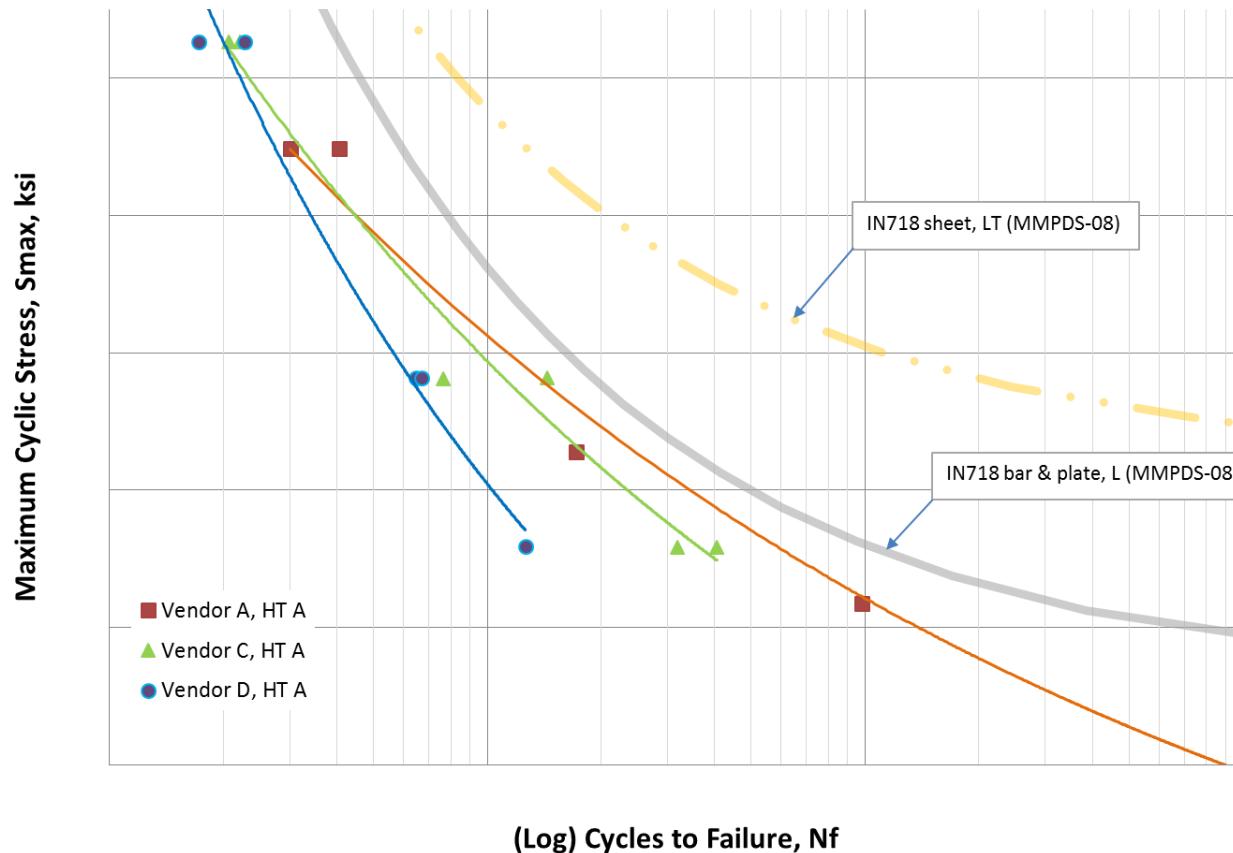
K_{Ic}

*No NASA-MSFC data was available.

- Fracture testing did not provide valid K_{Ic} (plane strain fracture toughness) results. The results are still useful, since they are characteristic of the thickness tested.
- K_{Ie} is provided as a reference.
- Z- and XY-orientations provided similar results for fracture toughness.
- All results were above K_{Ic} (NASGRO).



Vendor Results--Room Temperature High-Cycle Fatigue Tests
SLM IN718, HT A As-Built



- All tests were of heat treatment A specimens.
- As-built Vendors A and C results were in-family.
- As-built Vendor D was similar but lower than A and C.
- All of the as-built tests were below the MMPDS-08 reference curves.

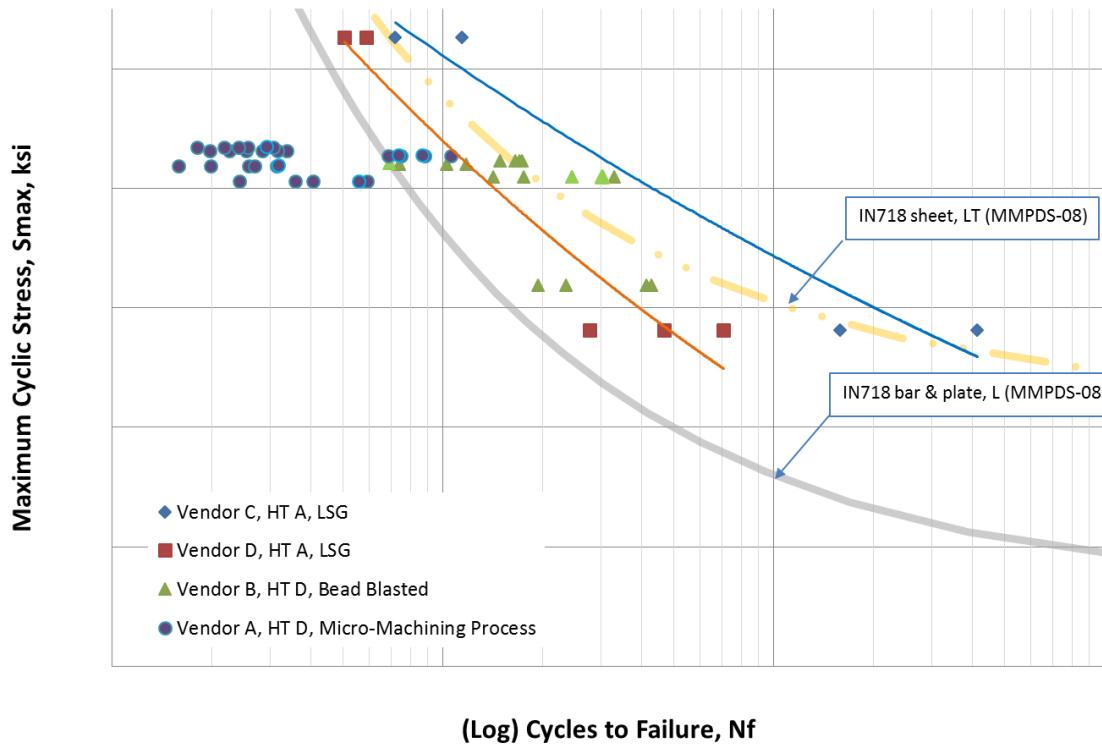
Power law fit lines have been inserted to help with visualizing the trends.



Vendor Results--Room Temperature High-Cycle Fatigue Tests

SLM IN718, HT A & D

Low-Stress Ground, Bead-Blasted, and MMP Finished Surfaces



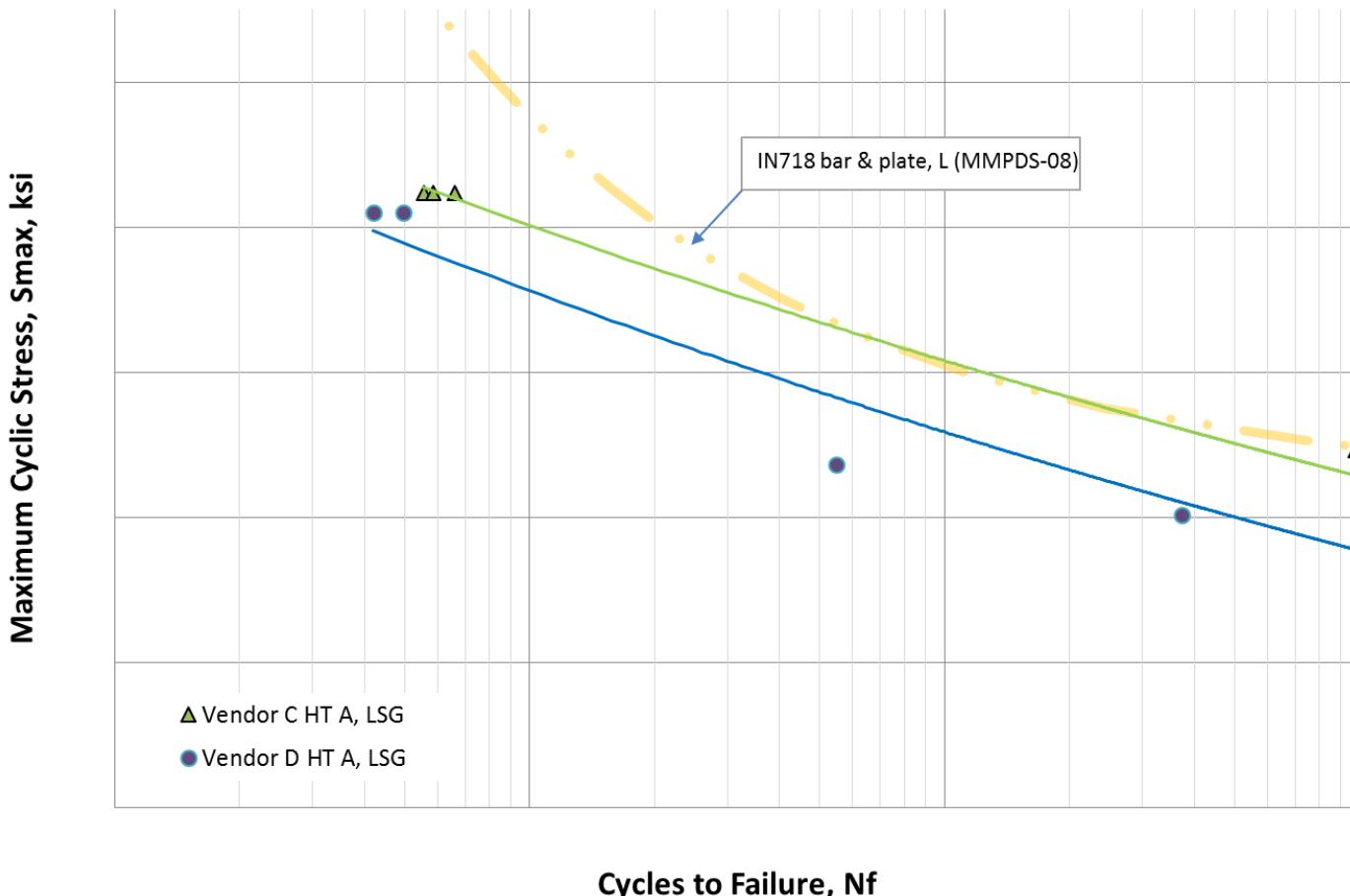
Power law fit lines have been inserted to help with visualizing the trends.

- Vendor C, heat treatment A, low-stress ground specimens performed as well as the published MMPDS-08 high cycle fatigue results.
- Vendor D, heat treatment A, low-stress ground specimens and Vendor B, heat treatment D, bead-blasted specimens performed better than the published results for IN718 bar and plate, but below the published results for IN718 sheet.
- Vendor A, heat treatment D specimens with micro-machining performed below all of the published information.



Vendor Results--1000F High-Cycle Fatigue Tests

SLM IN718, HT A, Z-Orientation
Low-Stress Ground Finished Surfaces



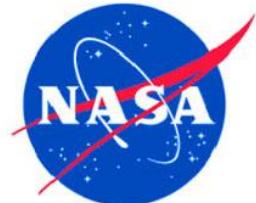
Power law fit lines have been inserted to help with visualizing the trends.

- All high-cycle fatigue data was below the published results at 1000F.



CONCLUSIONS

- Additive manufactured IN718 tensile, fracture, and high-cycle fatigue properties can match specified wrought material properties.
- Materials properties varied from vendor-to-vendor. The four vendors evaluated in this investigation provided specimens that met the specified wrought material tensile and fracture properties, but none performed as well as the high-cycle fatigue references in the as-built surface condition, and only one performed as well as the high-cycle fatigue properties of wrought IN718 sheet after surface treatments. For the lower reference, i.e., HCF of IN718 plate and bar, three vendors met the performance specified after surface treatments.
- Recommended build parameters for the most part produce properties that are in-family with wrought material properties, but for a given machine, they should be evaluated to insure that subsequent builds are produced with optimal properties.
- Evaluations of SLM-manufactured materials properties should be multi-variable investigations that can capture the co-variance of the build parameters. One approach to consider is “design-of-experiment” methodology.



RECOMMENDATIONS

- Use multi-variable testing methods (design of experiment) to better understand and optimize the build parameters.
- Evaluate the response of tensile properties to varied heat treatments.
- Investigate additional alloys.
- Develop a well-defined approach to flight certification.
- Establish closed-loop control capabilities that utilize feedback to better control the SLM process and ensure uniform results.